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NASA/DOE/DOD Nuclear Propulsion Technology Planning: Summary of FY 1991 Interagency Panel Results

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SUMMARY OF FY 1991 INTERAGENCY PANEL RESULTS**

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ABSTRACT

Interagency (NASA/DOE/DOD) technical panels worked in 1991 to evaluate critical nuclear propulsion issues, compare nuclear propulsion concepts for a manned Mars Exploration mission on a consistent basis, and to continue planning a technology development project for the Space Exploration Initiative (SEI). Panels were formed to address mission analysis, nuclear facilities, safety policy, nuclear fuels and materials, nuclear electric propulsion technology and nuclear thermal propulsion technology. This paper summarizes the results and recommendations of the panels.

INTRODUCTION

The NASA Lewis Research Center, Nuclear Propulsion Office (NPO) is leading a nuclear propulsion technology development project for manned Mars missions, with participation by other NASA Centers, and the Departments of Energy and Defense, to provide nuclear technology and nuclear facilities support. The project includes both nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) technology development.

The technology development project is guided by SEI mission requirements. These mission requirements will probably remain a "moving target" for some time as SEI studies continue and the mission architectures are defined. The project includes concept definition and systems engineering, (to ensure that the appropriate technologies are being developed), and enabling technology development, followed by extensive system testing to verify technology readiness. The project planning in 1991 aimed to develop the technology to "technology readiness level 6" - (TRL-6), full system ground testing complete by 2006.¹ More recent planning has focussed on a more near-term goal (TRL-6 by 2000 for NTP technology), and this option will be discussed in the concluding remarks of this paper.

Workshops were held in 1990 on Nuclear Electric Propulsion and Nuclear Thermal Propulsion technologies.^{2,3} Interagency panels of technical experts were assembled to assess the nuclear propulsion concepts and technologies based on mission benefit (i.e., performance), safety, technical risk, development schedule and cost. In FY 1991, six interagency technical panels were formed to address some of the key issues identified at the workshops and to continue to refine the technology project plans. Each of these technical panels prepared a final report.^{4,5,6,7,8,9,10,11} This paper is an "executive summary" of the results and recommendations of the six panels.

MISSION ANALYSIS PANEL

The mission analysis panel was chartered to provide consistent mission requirements and studies to permit a fair and consistent comparison of nuclear

propulsion concepts and a focus for the technology development plans. Reference missions were selected early in FY 1991 to focus the propulsion system technology requirements and enable an early definition of facility requirements. An "all-up" reference mission, one in which the complete expedition equipment, supplies, and astronauts are sent on a single space vehicle, was used to estimate major test facility requirements as shown in Table I. Subsequently, the Stafford Synthesis Group Report has recommended "split-sprint" manned missions to Mars.¹² The "split-sprint" mission, in which a cargo mission precedes the piloted mission, was studied extensively by the members of the Mission Analysis panel, including the effects of engine-out on mission abort scenarios.

Table I Reference Missions Were Selected to Develop Test Facility Requirements

| NTP | NEP |
|---|--|
| <ul style="list-style-type: none"> "all-up" mission (3) perigee burn (3) engine cluster 75,000 lb thrust each 1 1/2 hrs. total burn time 1/2 hr. max. single burn (8) Restarts/mission 2700 K exhaust temp. with appropriate safety & reliability margins 925 seconds Isp | <ul style="list-style-type: none"> "all-up" manned mission multiple missions (reusable) refurbish thrusters, replace propellant 10 MWe power 10 kg/kWe 400 mt IMLEO (2016) 250-300 days one-way transit 500-600 days opposition-class mission "split" missions → 400 days R.T. cargo → minimum energy |

Nuclear Electric Propulsion Missions

The panel studied performance tradeoffs associated with NEP systems, and some of the results are shown in Figure 1. These results compare initial mass in low earth orbit, IMLEO, as a function of round trip time, for various total propulsion system power levels and specific masses of 10 kg/kWe and 3 kg/kWe, for an opposition-class mission in 2016, with a 30-day stay time on Mars. Also shown on the figure are trip times for the piloted leg of the same mission in a split mode, a specific mass of 7 kg/kWe, and 15 MW power. Astronaut transit times of about one year are about the same as a nuclear thermal propulsion vehicle for this same mission.

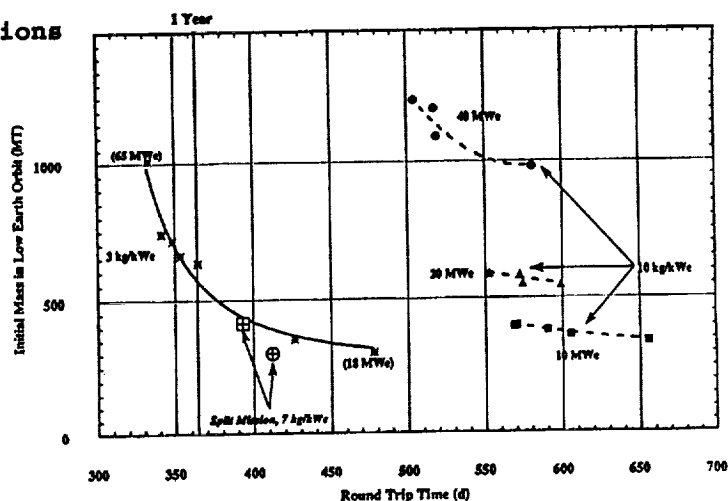


Figure 1 NEP Performance for Piloted Mars Opposition-Class Mission in 2016

Nuclear Thermal Propulsion Missions

The NTP "Split-Sprint" reference missions recommended by the Synthesis Committee are shown in Figure 2. A cargo flight could leave earth orbit in late 2011 on a minimum energy trajectory. Surface habitat and other equipment would be in place and checked out before astronauts left on an opposition class mission in early 2014. The astronauts would be subjected to 550 days of space travel from earth orbit to Mars and return, with a 90-day expedition on the Mars surface. At the same time, a second cargo flight could leave earth orbit early in 2014, in preparation for a conjunction-class mission in 2016. This mode would significantly reduce the astronaut space travel time to about 120 days outbound and 90 days return, (and reduce their exposure to harmful intergalactic cosmic radiation proportionately). Current mission planners have eliminated the opposition-class missions completely, because of the radiation hazards; thus, the initial piloted expedition will probably be a conjunction class, with about a 648 day expedition on the Mars surface.

Mission performance implications are summarized in figure 3, in which relative initial mass in low earth orbit (as a percent of a chemical-aerobrake system) is compared as a function of engine thrust-to-weight ratio, for various

propulsion system efficiencies. Specific impulse, I_{sp} , is a measure of the system thrust per propellant mass flow rate, and is a good measure of the performance of a space transportation system. These calculations were made for a system with 75,000 lb_f of thrust, and a single burn to leave earth orbit. As shown in the figure, I_{sp} is quite important in reducing initial mass (i.e., propellant) requirements, but above about 8-10, the thrust-to-weight ratio has very little effect.

Mission abort studies led to some important conclusions. First, a system with a single engine is subject to potential loss of crew if a non-repairable engine system failure occurs. With two or more clustered engines, the options for successful abort and safe return of the crew is enhanced significantly. Also, with clustered engines, in some cases options exist to successfully complete the mission, even with an engine out. Thus, multiple engines will contribute in a major way to astronaut safety and mission success.

Other studies were conducted of nuclear heating of system components, cooldown propellant requirements, and quantified figures-of-merit (FOM) for evaluating and comparing nuclear propulsion systems; much work remains to complete this evaluation, however.⁴

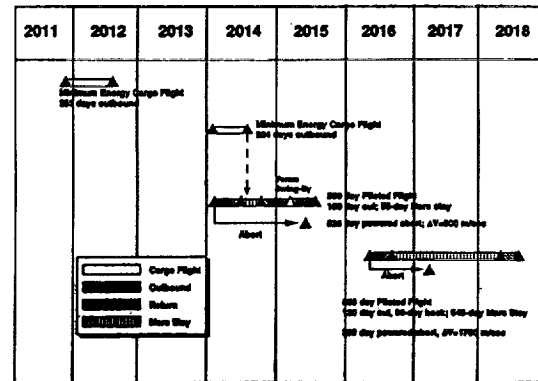


Figure 2 NTP Split-Sprint Reference Missions

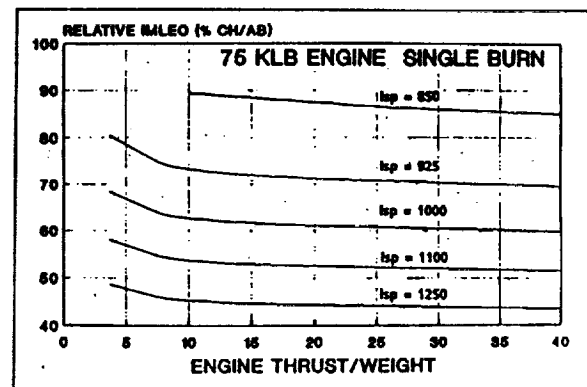


Figure 3 IMLEO as a function of T/W for a 75,000 lb System

NUCLEAR SAFETY POLICY WORKING GROUP

A joint interagency Nuclear Safety Policy Working Group (NSPWG) was formed to develop a policy on nuclear propulsion safety. The recommended safety policy follows:

"Ensuring safety is a paramount objective of the Space Exploration Initiative nuclear propulsion program; all program activities shall be conducted in a manner to achieve this objective. Stringent design and operational safety requirements shall be established and met for all program activities to ensure the protection of individuals and the environment. These requirements shall be based on applicable regulations, standards, and research. The fundamental program safety philosophy shall be to reduce risk to levels as low as reasonably achievable.

A comprehensive safety program shall be established. It shall include continual monitoring and evaluation of safety performance and shall provide for independent safety oversight. Clear lines of authority, responsibility, and communication shall be established and maintained. Furthermore, program management shall foster a safety consciousness among all program participants and throughout all aspects of the nuclear propulsion program."

Several SEI nuclear propulsion program flight safety requirements are recommended for use by program safety management, in system design and development, and program planning.

- (1) *The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, for which negligible radioactivity is produced.*
- (2) *The reactor shall be designed to remain shut down prior to the system achieving its planned earth orbit (safe for reactor startup operations).*
- (3) *Inadvertent criticality shall be precluded for both normal and credible accident conditions.*
- (4) *Specific requirements are recommended for radiological release and exposure for both routine operations and for accident scenarios.⁵ These requirements ensure astronaut safety and spacecraft functionality, and will ensure that even if a malfunction would occur during space operations, no environmental impact would occur on the earth surface.*
- (5) *Safe disposal of spent nuclear systems shall be explicitly included in SEI mission planning.*
- (6) *Specific requirements are included to ensure that return of a reactor to the earth is not a planned mission event, and, in an unlikely accidental entry, the reactor must remain subcritical, intact, and radioactivity shall be confined to a local area to limit radiological consequences, or shall be fully dispersed.*
- (7) *Positive measures shall be taken to control and protect the nuclear system and its special nuclear materials from theft, diversion, loss, and sabotage.*
- (8) *Risk identification and reduction efforts shall be included in the program, and probabilistic goals shall be demonstrated through testing and analysis.*

Recommendations are also included for controlling hazards associated with ground testing for flight safety validation, and for ground facility and equipment safety and environmental compliance.

FUELS/MATERIALS TECHNOLOGY PANEL

This panel was chartered to define a fuels and materials technology program for NTP and NEP reactor systems.⁶ An early output from this panel described facility requirements for nuclear fuel testing. Detailed test objectives were defined for a wide range of possible fuel types and reactor types. Fuels and materials technology requirements included (for NTP): operating lifetimes to 10 hours, operating temperatures to 3000 K or higher, as-low-as-reasonably-achievable, (ALARA) fission product release, and compatibility with hydrogen. For NEP, temperatures are much lower but reactor operating life is much longer (years) and fuel burnup and possible swelling issues must be considered, and various other reactor coolants must be considered. Low mass and system reliability will be key drivers.

The various fuel types were categorized into about four to six types. Technical feasibility issues associated with these fuel types include: maximum temperature and life tradeoffs associated with corrosion, cracking and fission product release; high-temperature vaporization, melting, and composition stability; element-to-element interactions; and power-to-flow matching, stability and control. Several reactor concepts incorporate inherent active flow control to ensure coolant integrity (NERVA and prismatic cermet concepts, for example), while other concepts have "passive" flow control (such as particle bed and wire core reactors); these concepts must demonstrate flow stability and control over all operating conditions, to demonstrate "proof-of-concept."

A fuels test and development plan is presented for each of the six fuel types. A summary of the fuel plan for NTP concepts is shown in figure 4. The

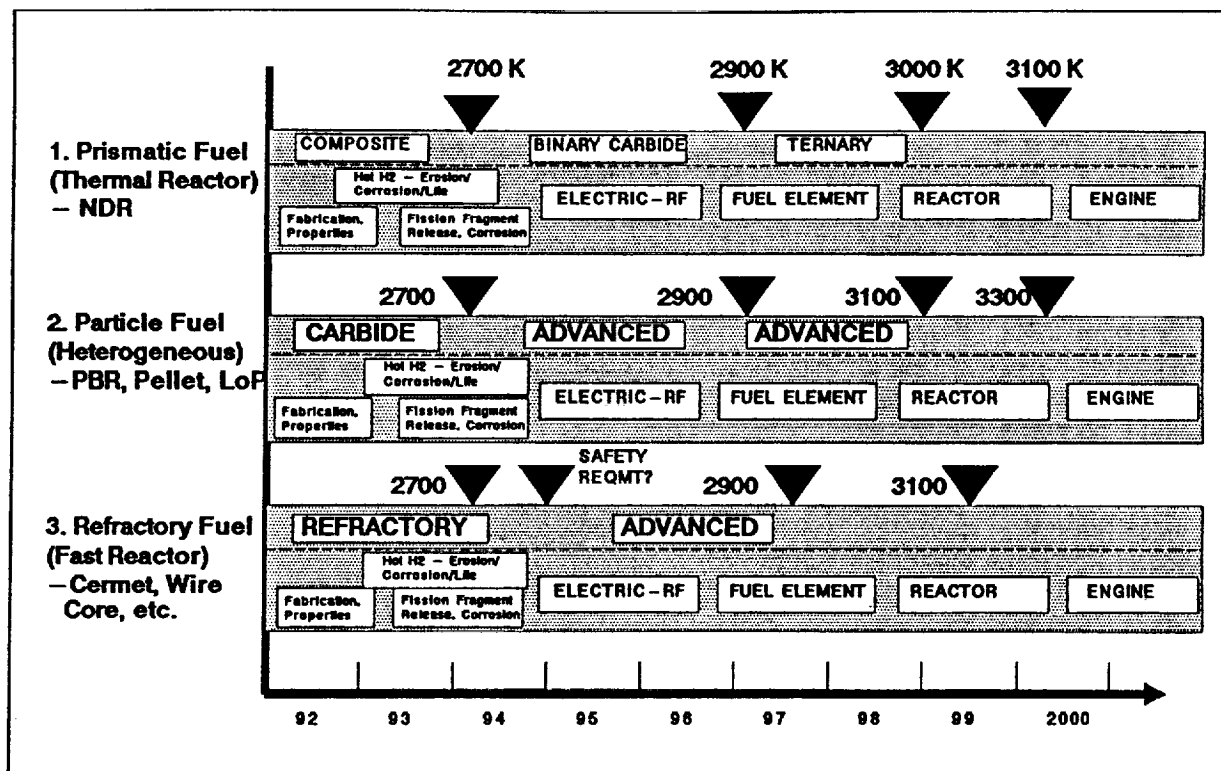


Figure 4 Summary NTP Fuel Development Plan

plan includes fuel fabrication and production development. Fuel property characterization includes chemical properties such as density, melting points, specific heat, thermal conductivity, tensile and compressive strengths, and chemical compatibilities with other materials and propellants. This characterization includes design-specific data gathering, such as coating thickness effects, geometry effects and fuel loading and burnup effects. Detailed knowledge of fuel properties is essential for design, concept evaluation, and safety, probabilistic risk analysis, and reliability analysis. Non-nuclear testing of fuels, such as electrical or RF heating will be included to support the expensive nuclear heating tests, and is expected to provide useful screening data, transient stress verification, and compatibility data for relevant coolants.

Nuclear testing will be conducted in several phases. The first is based on capsule testing many small samples in existing experimental reactors. Fuel designs can thus be screened over a range of temperatures and power generation rates. Next, loop tests will be conducted with full sized fuel elements, in appropriate nuclear environments, with coolant flow/power matching. These will be followed by tests in a driver core (a nuclear furnace) where the actual operating conditions of the fuel can be reproduced. Since this testing is expected to be very expensive, the number of fuel elements, and types of fuels will be limited to those that show the most promise. Finally, integrated engine tests will be undertaken.

The fuels and materials test plan describes efforts required for each of the six different fuel forms, and would create a comprehensive database from which to design specific reactor concepts and eventually downselect to one or two system concepts. While the need for fuel production facilities, a driver core (nuclear furnace), and integrated engine test facilities were recognized and discussed, planning for these facilities and tests were considered by the Facilities Panel.

NUCLEAR ELECTRIC PROPULSION TECHNOLOGY

The NEP Technology Panel was chartered to characterize NEP system options, using common, consistent ground rules and assumptions, and to make recommendations for an NEP technology development plan.⁷ Five major sub-systems usually make up an NEP system: reactor, power conversion, thermal management, power management and distribution (PMAD), and thruster. Many component options have been identified that could be used to make up the NEP system, but an "optimized" system has not been designed, nor is the technology in hand for a manned NEP mission to Mars. A conceptual design study is proposed early in the program to focus on an optimized system design, and to help focus the technology development activities.

The proposed NEP technology development plan is evolutionary, in that it contains interim milestones and missions to verify the technology readiness in low-power, interplanetary mission applications first, and then progress to the more challenging Mars cargo and piloted missions. The NEP technology development plan is highly integrated with the existing NASA/DOE/DoD SP-100 space reactor program and the SP-100 technology is an effective "jumping off" point from which the NEP manned systems may be developed. A summary test plan is included in figure 5 for MW-class NEP systems.

The major NEP technical challenges include: overall system mass minimiza-

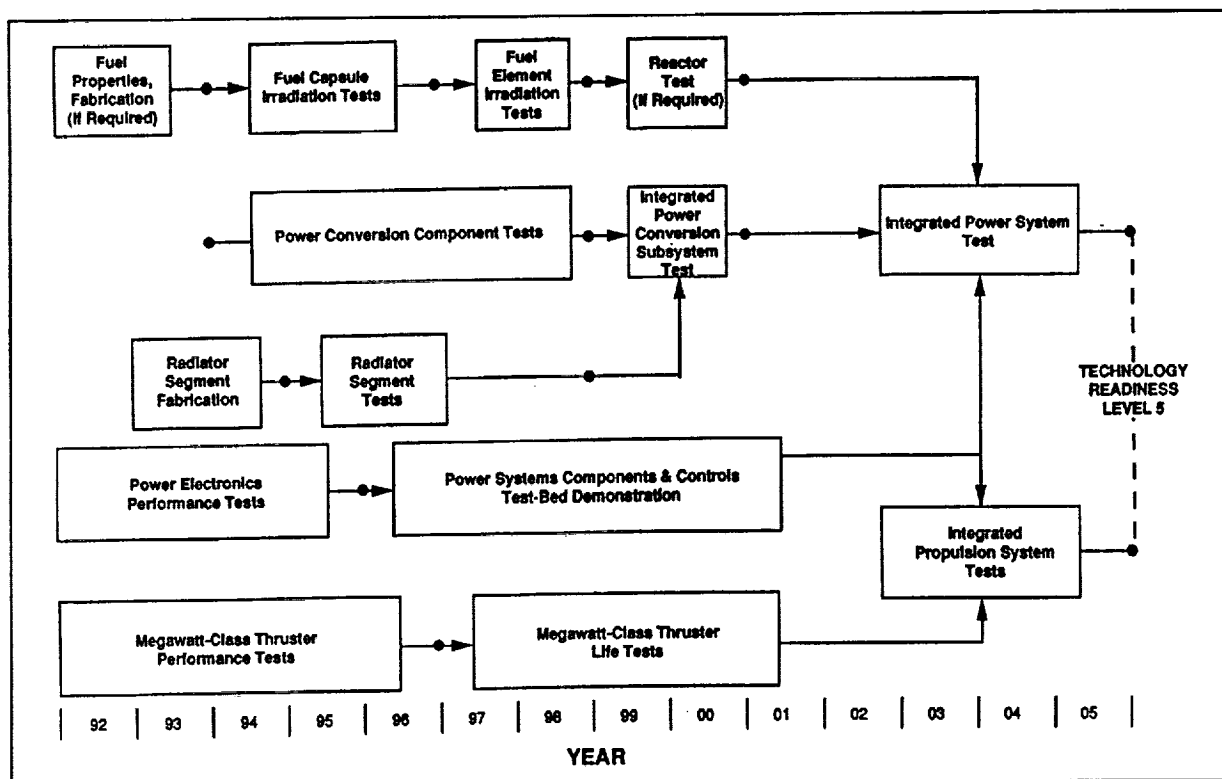


Figure 5 Summary Technology Test Plan for MW NEP

tion; high power, high temperature reactors, turbines and radiators; high burnup fuels and reactor designs; efficient, high temperature power conditioning; efficient, long life thrusters; and effective integration of the NEP components. The high system specific impulse, however, makes the system ideally suited for long missions where minimum propellant usage is critical.

The NEP panel made the following recommendations:

- (1) The U.S. should plan and implement an evolutionary technology development project in NEP, directed toward providing the technology for a manned mission to Mars, while including interim project milestones for near earth, interplanetary robotic and lunar and Mars cargo missions.
- (2) From the project outset, efforts should be initiated to determine performance and life limits of kilowatt-class and mega-watt-class electric thrusters; determine efficiencies, lifetimes, and radiation tolerance of high temperature power electronics; and address fundamental technology issues associated with lightweight heat rejection systems.
- (3) Accelerate the schedule for a ground test demonstration of the SP-100 space reactor and power conversion technologies in the late 1990s.
- (4) Perform a systems-subsystem trade study early to identify critical NEP technologies and to specify detailed technology requirements for system safety and performance.
- (5) Demonstrate high power, low mass, dynamic power conversion technologies.
- (6) If justified by system trade studies, develop and demonstrate new reactor technology at higher temperatures than SP-100.
- (7) Characterize the performance and lifetime of the current SP-100 fuels technology at higher temperatures for possible application to high performance NEP systems.
- (8) Assess candidate facilities for NEP power subsystem and propulsion subsystem testing for their suitability to meet ground testing requirements.
- (9) Provide a forum for the continued involvement of U.S. experts in all technology areas of NEP as the project is implemented.

TEST FACILITIES PANEL

The Test Facilities Panel was chartered to identify nuclear propulsion test facility requirements and options early in the panel deliberations, since major facilities are known to be long-lead-time elements of a test program.⁹ Reference mission requirements were provided by the Mission Analysis Panel, and test requirements were provided by the NTP, NEP, and Fuels/Materials Panels. A number of potential test sites were visited, and a significant database was established for facilities that may be used in the technology development project.¹⁰ A major panel effort evaluated test requirements and defined specific test objectives. Various test site alternatives were visited and evaluated. Finally, a facility development strategy, schedule and preliminary cost estimates were developed.

Major NEP test facilities include a MW-class thruster life test facility. Also, if a new reactor is found to be required, a new reactor test facility might be required. Major NTP test facilities include an NTP fuel element tester (nuclear furnace) capable of testing a wide range of element concepts at rated power and life, an NTP system ground test facility with multiple cells for reactor and engine tests, and flight system engine qualification tests, (see Fig. 6). The NTP test facilities will include full effluent cooldown and cleanup to ensure environmental compliance. It was estimated that the earliest that a nuclear furnace facility could be completed is 1997, and the full system ground test could be available in 1999.

NUCLEAR THERMAL PROPULSION TECHNOLOGY

The NTP Technology Panel was chartered to evaluate nuclear thermal propulsion concepts on a consistent basis, and to continue technology development project planning for nuclear propulsion for the Space Exploration Initiative.¹¹

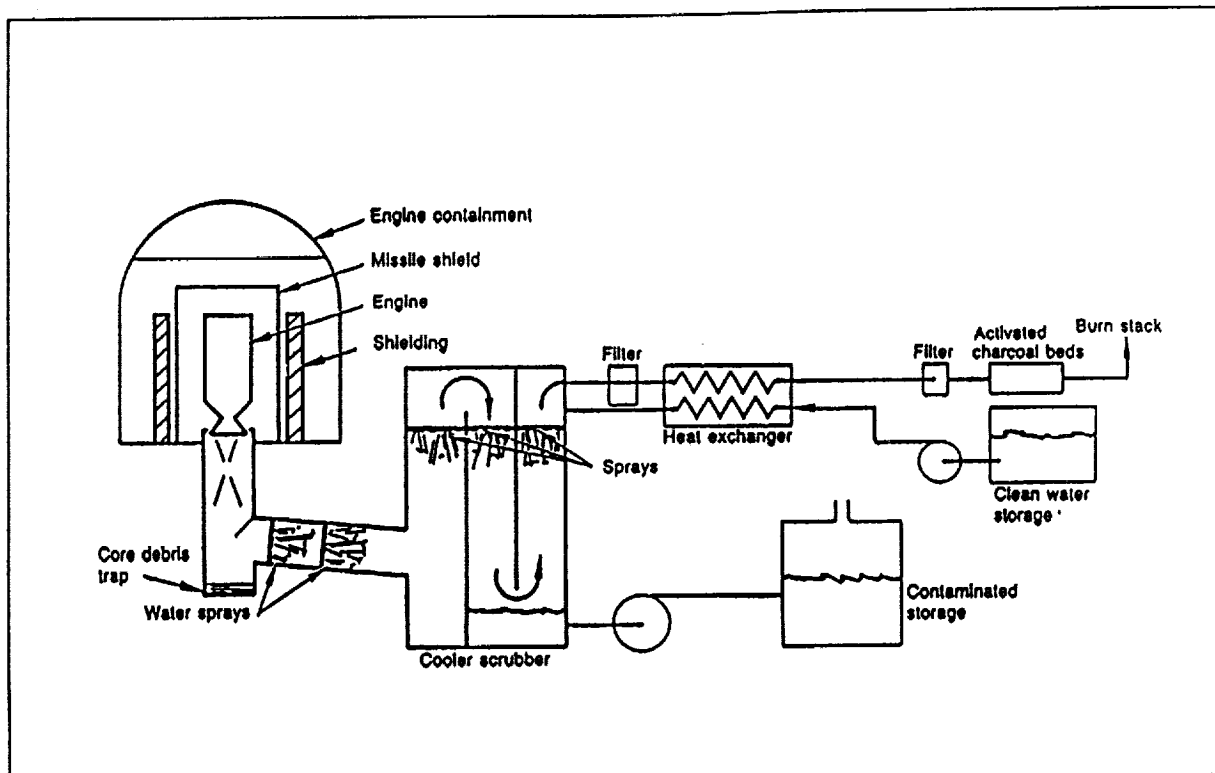


Figure 6 NTP Full System Ground Test Facility Schematic

Concepts were categorized based on probable technology readiness date. It was the consensus of the panel that any of the solid core reactor types could be developed to TRL-6 by 2006, provided that adequate funding is provided, and proof-of-concept issues are overcome. A faster development option was also considered, but the panel agreed that only the NERVA-derived concept could be developed for a first NTR flight in 2000-2005.

A "concurrent engineering" approach was recommended, in which test facility design and construction would proceed in parallel with technology development, concept design, and flight system design and hardware construction, (see Fig. 7). Thus, the technology validation hardware would be actual flight-design hardware, saving many years on the development of flight hardware, and subsequent acceptance and qualification testing. Figure 7 shows the schedule required to reach TRL-6 in 2006, for a first flight in 2008. For TRL-6 in 2000 and first flight in 2002-2005, phases III and IV would have to be started sooner.

Innovative concept "proof-of-concept" tests and analyses were defined for next generation NTP concepts, that could provide substantial performance improvements. Further studies will be required, and are currently underway to provide a consistent comparison of all of the NTP concepts.

The NTP panel agreed that the highest priority technology development efforts should be (1) high temperature fuels and materials development, (2) long lead time facilities design and construction for technology validation testing, and (3) conceptual design studies to focus the technology development efforts. Instrumentation development, neutronics, controls, health monitoring and diagnostics system integration will also be very important and should be included in the project from the beginning.

CONCLUDING REMARKS

An extensive interagency panel activity was conducted in FY 1991 to further

define technology plans for nuclear propulsion for SEI, and to make recommendations regarding specific issues identified at 1990 workshops.

NTP Schedule

President Bush has announced a goal to have astronauts on Mars by 2019. Using a business-as-usual approach, in which technology-readiness is followed by up to 10 years of "advanced development," acceptance testings and flight qualification testing, this led to the target of TRL-6 in 2006 that was used for the panel activities. It was recognized at the NTP workshop in 1990 and reiterated by the NTP panel that this schedule could be significantly reduced

by using a "concurrent engineering" approach. This approach is considered to be very attractive to Michael Griffin, the new NASA Associate Administrator for Exploration, and he asked NPO to evaluate this "Fast track" option.

These studies have been initiated for a TRL-6 in 2000, using NERVA-derived technology as a baseline, leading to first NTR flight in 2002-2005. Other reactor concepts will also be considered, but to meet this schedule, an authority to proceed with flight system hardware development will be required in about 1994; therefore, to be considered concepts must have demonstrated "proof-of-concept" by that time, must offer similar safety and reliability, and equal or better performance than the NERVA-based reference system.

NEP Schedule

The very high specific impulse of NEP systems offers very attractive options for the NASA science community since very ambitious missions to the outer planets can be done that would not be attempted with chemical systems. Therefore, the NASA Office of Space Science and Applications has strongly recommended the development of NEP Technologies for their needs in the next decade. The NEP technologies identified by the NPO to meet OSSA mission needs are SP-100 and ion electric propulsion. Plans have been made to develop and ground test these technologies by 2000-2001. NEP for Mars and lunar exploration does not currently enjoy the same high priority in the Office of Exploration. Studies have shown that NEP can offer significant benefits for these missions, however, and NPO believes that NEP should be studied and developed for these Code X missions.

In conclusion, the interagency panels have been very useful to the project planning team, and their efforts are sincerely appreciated. The authors strongly recommend that the U.S. move forward with SEI and with nuclear propulsion systems to enable the SEI vision to become a reality.

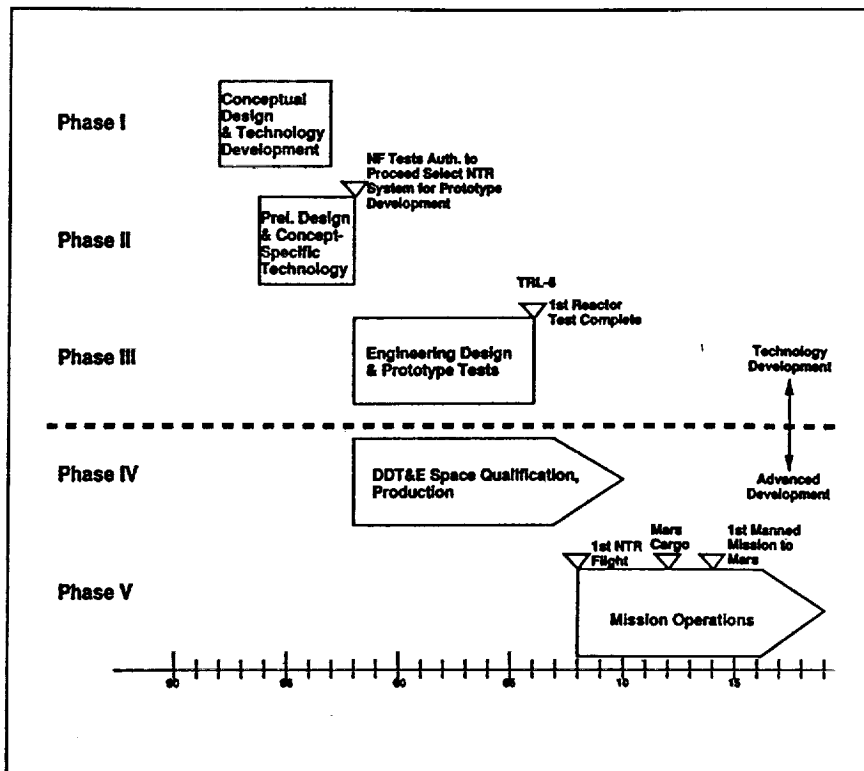


Figure 7 NTP Concurrent Engineering Approach for TRL-6 in 2006; First NTR Flight in 2008

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